DELAMINATION DAMAGE OF CARBON FIBER-REINFORCED POLYMER COMPOSITE LAMINATES UNDER CYCLIC SHEAR-INDUCED LOADING CONDITIONS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

School of Mechanical Engineering
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OCTOBER 2018

To my beloved
Mom, Dad, and Wife for
their endless love and support….

ACKNOWLEDGMENT

Alhamdulillah, I have completed writing this thesis but of course with the help and support from fantastic peoples around me. First and foremost, I wish to express my heartfelt gratitude to my supervisor, Prof. Dr. Mohd. Nasir Tamin for his professional guidance and support in academic and in real life. I am very indebted to his patience and invaluable advices that inspired me to see things positively and felt honoured with his confidence and trust on my ability.

I would also like to thank my co-supervisor, Dr. Wong King Jye and a special thanks to Dr. Seyed Saeid Rahimian Koloor for providing me with valuable suggestions and recommendations. My sincere thanks to all my friends and colleagues for their cheerfulness and fun. Thank you for the great moments that we have shared together especially Mahzan, Amirul, Sharul, Izzudin, Zal, Faizah, Marhaini, Azisyahirah, Intan, Nurasykin and all members of Computational Solid Mechanics Laboratory (CSMLab). Only we know the ups and downs in this so called 'Graduate Life'. Grateful acknowledgement is also made for financial support by the Ministry of Higher Education (MOHE) Malaysia and Universiti Tun Hussein Onn Malaysia.

Last but not least, a special thanks to my family for their continuous support and encouragement especially to *Mak*, *Baba* and my wife, Hafizah Ibrahim. This dissertation is the product of so much more than five years and my family has supported me through it all. There are so many people to whom I am indebted for support and encouragement.

I thank you all…

ABSTRACT

Interface delamination is a major failure mode induced by in-plane shear stress frequently encountered in carbon fiber-reinforce polymer (CFRP) composite laminates structures. This failure process under monotonic loading has been successfully described using cohesive zone model (CZM). Many previous CZM approaches for cyclic case were considering damage parameters based on a crack growth relation which has some disadvantages for predicting a non-linear crack growth. In addition, the previous CZM approach lacks ground in understanding the physics underlying the delamination process and effect of stress ratio. The objective of the study is to extend the existing CZM to account for the delamination damage evolution of CFRP composite laminates under cyclic shear-induced loading conditions named as cyclic cohesive zone model (CCZM). In this respect, the fatigue damage response and the residual interfacial properties associated with the development of the CCZM are established under cyclic shear-induced loading condition. A series of Mode-II-type tests were performed on pre-fatigued end-notched flexural (ENF) beams of CFRP composite laminates, $[0]_8$ for different applied load ratio conditions (R = 0.1, 0.15 and 0.25) to induce only interlaminar damage at the pre-existing delamination interface crack front. Subsequent quasi-static test to catastrophic failure establishes the characteristic residual strength responses of the damaged specimen. A hybrid experimental-computational approach was introduced to obtain the residual interlaminar properties for all the loading cases. A normalized gradual degradation rule was used to present the degradation for interlaminar shear strength (S), penalty stiffness (k_p) and the critical Mode-II energy release rate (G_{IIC}) which cover the wide range of interlaminar failure mode from wear out to sudden death. This interlaminar properties degradation model can describe the characteristic evolution of the interlaminar damage response and the degradation of CCZM properties under cyclic shear-induced loading case. The interlaminar properties degradation model together with the CCZM model is coded by using user-define material model (UMAT) subroutine to implement in ABAQUS finite element analysis (FEA) software. This model had been used to simulate under 3-point bending cases and compared with the experiment results. Result had shown that the comparison between the FE simulation and the experiment fatigue load-life cycles for CFRP composite laminate interfaces are close with the difference of less than 1% and shows a very successful verification of the modified CCZM model to simulate the interlaminar damage evolution and failure response. Besides that, an independent validation had been run to validate the performance of interlaminar properties which were obtained in the study. A load-deflection response under 3-point bending case was simulated based on $[0]_{16}$ ENF specimen under identical load cycle parameters and compared with the measured experiment results. Result shows that the peak load differences between the experiment and simulation is less than 6%. From the study, the capability of CCZM model for cyclic case has been demonstrated by linking interlaminar properties degradation with damage mechanics approach. This will help in understanding the physics underlying the delamination process and effect of stress ratio.

ABSTRAK

Pelekangan antara lamina adalah mod kegagalan utama yang disebabkan oleh tegasan ricih sesatah yang seringkali dialami oleh struktur lapisan komposit polimer bertetulang-gentian karbon (CFRP). Proses kegagalan ini di bawah beban ekanada telah berjaya dihuraikan menggunakan model zon jelekat (CZM). Banyak pendekatan CZM terdahulu untuk kes berkitar telah mengambilkira parameter kerosakan berdasarkan hubungan pertumbuhan retakan yang mana mempunyai beberapa kelemahan dalam meramal pertumbuhan retak bukan lelurus. Selain dari itu, pendekatan CZM sebelum ini kurang mempunyai asas pemahaman fizik berdasarkan proses pelekangan dan kesan nisbah tegasan. Objektif kajian ini adalah untuk memperluaskan CZM sediaada bagi mengira evolusi kerosakan pelekangan pada lapisan komposit CFRP yang disebabkan oleh keadaan beban kitaran ricih-teraruh yang dinamakan model zon jelekat berkitar (CCZM). Dalam hal ini, tindak balas kerosakan lesu dan sifat-sifat sisa antara lamina yang dikaitkan dengan pembangunan CCZM dihasilkan berdasarkan keadaan beban kitaran ricih-teraruh. Siri ujian jenis Mode-II dijalankan pada rasuk lenturan takuk-hujung (ENF) daripada lapisan komposit CFRP, $[0]_8$ yang dipra-lesu pada keadaan nisbah beban berbeza (R = 0.1, 0.15 and 0.25) untuk mengaruh kerosakan antara lamina pada hadapan retakan antara lamina yang sediaada. Seterusnya ujian kuasi-statik sehingga kegagalan bencana menetapkan ciri-ciri tindak balas sifat-sifat sisa kekuatan spesimen yang rosak. Kaedah hibrid pengkomputeran-eksperimen diperkenalkan bagi mendapatkan sifat-sifat sisa antaramuka pada kesemua kes pembebanan. Aturan penurunan beransur ternormal telah digunakan untuk mewakili kemerosotan kekuatan ricih antara lamina (S), kekukuhan denda (k_p) dan Mod-II kritikal kadar pelepasan tenaga (G_{IIC}) yang merangkumi pelbagai mod kegagalan antara lamina dari haus sehingga kegagalan mengejut. Model sifat penurunan antara lamina ini akan menghuraikan evolusi ciri tindak balas kerosakan antara lamina dan kemerosotan sifat-sifat CCZM di bawah kes beban kitaran ricih-teraruh. Model sifat penurunan antara lamina bersama-sama dengan model CCZM dikodkan dengan menggunakan model bahan takrif-pengguna (UMAT) subrutin untuk dilaksanakan dalam perisian analisis unsur terhingga (FEA) ABAQUS. Model ini telah digunakan untuk mensimulasi kes lenturan 3-titik dan dibandingkan dengan keputusan eksperimen. Keputusan telah menunjukkan bahawa perbandingan antara simulasi FE dan eksperimen kitaran hayat-beban kelesuan untuk lapisan komposit CFRP dengan perbezaan kurang dari 1%. Ini menunjukkan pengesahan yang sangat berjaya terhadap model CCZM yang diubah suai untuk mensimulasikan evolusi kerosakan antara lamina dan tindak balas kegagalan. Selain itu, pengesahan bebas dijalankan untuk mengesahkan prestasi sifat antara lamina yang telah diperolehi dalam kajian ini. Tindak balas beban-permesongan di bawah kes lenturan 3-titik telah disimulasi berdasarkan spesimen ENF $[0]_{16}$ di bawah parameter kitaran beban yang sama dan dibandingkan dengan data eksperimen yang diukur. Keputusan menunjukkan, perbezaan beban puncak di antara eksperimen dan simulasi adalah kurang daripada 6%. Dari kajian ini, keupayaan model CCZM untuk kes kitaran telah dibuktikan dengan menghubungkan sifat penurunan antara lamina dengan pendekatan mekanik kerosakan. Ini akan membantu memahami dasar fizik proses pelekangan dan kesan nisbah tegasan.

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LIST OF ABBREVIATIONS

ASTM	-	American society for testing and materials
CAE	-	Computer aided engineering
CCZM	-	Cyclic cohesive zone model
CDM	-	Continuum damage mechanics
CFRP	-	Carbon fiber-reinforced polymer
CLS	-	Crack lap shear
CZM	-	Cohesive zone model
ENF	-	End-notched flexure
FE	-	Finite element
FEM	-	Finite element method
FRP	-	Fiber-reinforced polymer
LEFM	-	Linear elastic fracture mechanics
QUADSCRT	-	Quadratic traction damage initiation variable
SDEG	-	Scalar stiffness degradation
SDV	-	Solution-dependent state variables
UD	-	Unidirectional
UHMW	-	Ultra high molecular weight polyethylene
UMAT	-	User-define material model
VCCT	-	Virtual crack closure technique

LIST OF SYMBOLS

a	-	Crack length
b	-	Width
d	-	Fatigue degradation parameters
f	-	Frequency
G_c	-	Critical energy release rate
G_{Ic}	-	Mode-I (crack opening) critical energy release rate
G_{IIc}	-	Mode-II (in-plane shearing) critical energy release rate
G_{IIIc}	-	Mode-III (out-of-plane shearing) critical energy release rate
G_I	-	Mode-I energy release at failure
G_{II}	-	Mode-II energy release at failure
G_T	-	Total energy release rate
k	-	Penalty stiffness
k_n	-	Mode-I Penalty stiffness
k_p	-	Mode-II Penalty stiffness
k_p^f	-	Penalty stiffness in shear direction, fatigue loading
L	-	specimen span
N	-	Tensile strength
n	-	Number of cycles
N_f	-	Fatigue life
P	-	Load
P_{max}	-	Maximum cyclic level
P_{min}	-	Minimum cyclic level
P_{mean}	-	Mean load
P_{amp}	-	Load amplitude
R	-	Load ratio
S	-	In-plane shear strength

S_{max}	-	Maximum stress
S_{min}	-	Minimum stress
S_a	-	Stress amplitude
S_m	-	Mean stress
T	-	Out-of-plane shear strength
t	-	thickness
η	-	Exponent for B-K criterion
δ	-	Deflection
δ_n^0	-	Mode-I relative displacement at damage onset
δ_s^0	-	Mode-II relative displacement at damage onset
δ_n^f	-	Mode-I relative displacement at fracture
δ_s^f	-	Mode-II relative displacement at fracture
σ_{33}	-	Normal stress
τ_{13}	-	In-plane shearing stress
τ_{23}	-	Out-of-plane shearing stress

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Fiber-reinforced polymer (FRP) matrix composites consist of thermoset or thermoplastic resin matrix reinforced by much stronger and stiffer fibers such as carbon, glass and ultra-high-molecular-weight (UHMW) polyethylene fibers. Carbon fiber-reinforced polymer (CFRP) composites are typically hired in advanced applications which includes the aerospace, automotive, marine, sport and construction applications. Modern aircraft design like the Boeing 787 were among the aircraft representing the maximum use of this material in the primary structures such as wing skins and fuselage which are made of CFRP composite. The increment usage of CFRP composites is derived from their advantages such as high strength, light weight, corrosion resistance, chemical resistivity, electrical conductivity and many more. In this case, it is very necessary to predict the failure response of CFRP composite during the design and analysis processes of the structures. There are two approaches to predict the failure response which are by using the experimental and numerical approaches. Most of the experimental procedure is very costly and time consuming, especially when dealing with complex loading. For the industry applications, CFRP structural components are usually subjected to complex fatigue loading histories [1] specified by various amplitude, stress ratio, frequency and waveform of the stress cycles during service. However, deficiencies in current lifetime prediction methodologies for these materials often require large factors of safety that need to be adopted to ensure safety of the materials in the application. Therefore, composite structures are usually overdesigned and require an extensive prototype testing that need to be used for a proper lifetime prediction. By using the finite element (FE) tools, the lifetime prediction of CFRP material could be done to improve the design by using less number of expensive physical tests.

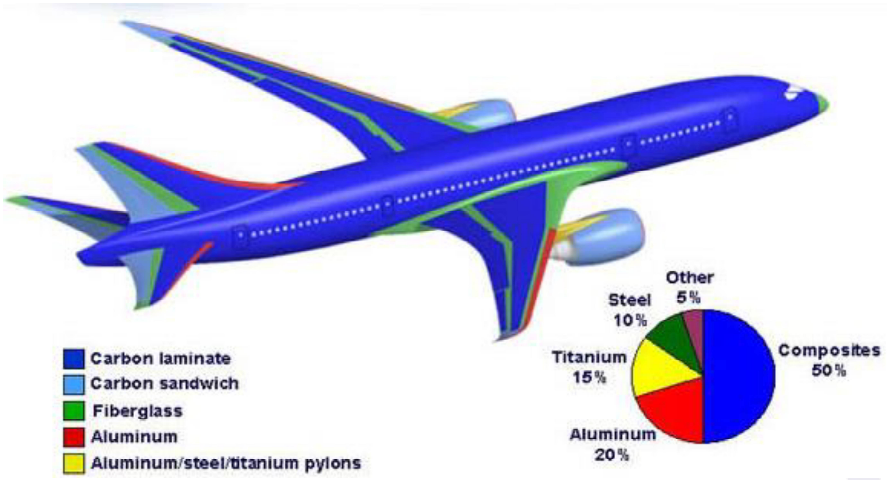

Figure 1.1: Typical use of composite in aircraft Boeing 787 [2].

The knowledge of Computer Aided Engineering (CAE) is used to evaluate the material's resistance under different loading conditions in simulated service environment. It is well known from the aerospace industry that composite structures are sized based on the building block approach [3]. This methodology is described in Figure 1.2, with the pyramid concept. The main idea is to build the knowledge on the material and structural behavior step by step, starting from the fundamental stage at the coupon level up to the full-scale structures. It has been observed over the years that simulation, and especially models based on the finite element method, are more and more used in the different stages of the pyramid, trying to become a companion of the physical tests. It is indeed evident that tests can be expensive when repeated several times for different material configurations (e.g. different stacking sequences) or when changes in the components geometry or loading conditions. Therefore, by using virtual testing can help reduce the product development costs and time. To fulfil this requirement, finite element analyses must be predictive. If this condition is satisfied, simulation can then replace some physical tests.

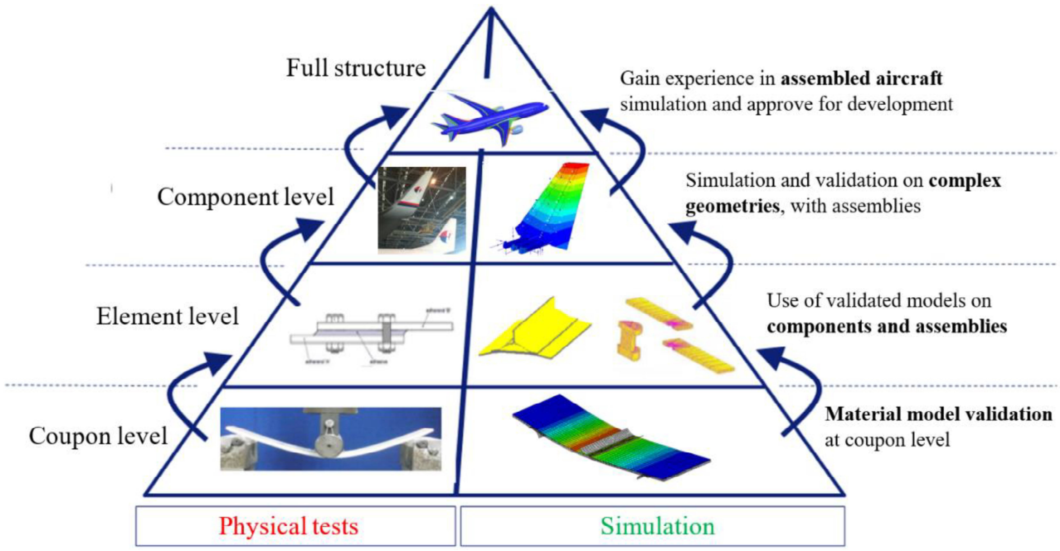

Figure 1.2: The building block approach applied to aerospace composite structures.

Currently, the CFRP composite simulation under monotonic and quasi-static loading has been well established in the literature. However, under cyclic or fatigue failure is still considered as an open topic for further investigation. There is different mode of failure that can be occur during the operational time such matrix yielding, matrix cracking, fiber/matrix interface debonding, fiber pull-out, fiber fracture and interface delamination. Interface delamination is one of the most critical issues face by the CFRP composite laminates under fatigue loading since most of the structures have a relatively weak ply-to-ply interface strength. Therefore, this thesis had described a damage mechanics concept for predicting the fracture of CFRP composite laminates under cyclic shear-induced loading conditions. Delamination under cyclic shear-induced loading condition had been considered in this research due to the fact that many composite structures are far more sensitive of being loaded in shear rather than in tension [4-8]. Besides, Mode-II delamination in composite laminates is a major matrix-controlled failure mode induced by out-of-plane flexural loading. The methodology which had been described in this thesis will be a useful guidance to predict a larger scale of specimen or structure using finite element software which had been integrated with proper user-written subroutine.

1.2 Background and Rationale

CFRP matrix composites belong to a new advanced material developed that are strong, lightweight, low densities, and not easily corroded. In the transportation industry, by reducing the vehicle weight will help to reduce the fuel consumption and has become one of a main goal in this sector since the fuel price in this world are being increased rapidly. This can be achieved by substitution of metal-based alloys, commonly used in aerospace and automotive structures with lighter weight material such as CFRP. The rapid increment in CFRP usage from 20% in 1990 (A320) to over 60% in 2010 (A380) for aircraft structures and high lift components is demonstrated [3]. In military vehicles, composite structures have an advantage in stealth application since this material are transparent to radar. Beside transportation industry, this CFRP composite laminates have helped to develop construction sector for bridges and precast concrete. In addition, CFRP composites offer flexibility in design through sequencing of pre-impregnated laminates for tailored strength and stiffness properties in particular loading direction. The relative low consolidation or curing temperature further lowers the manufacturing cost of the part. The challenge is to consider the design tradeoffs in choosing the lightest material that still meets the strength requirements of the part while maintaining the cost effectiveness. The reduced through-life support cost of the composite structures must also be considered. This is what the industry need which is to evaluate the resistance of the material under various loading conditions such as quasi-static, fatigue and impact loading with evolution of mechanical damage under simulated service environment. This calls for evaluation of the material's resistance to quasi-static, impact and fatigue loading along with mechanical damage evolution in simulated service environment. Simple mechanical tests of the composite laminates coupons, under various loading conditions such as compression, tension, shear and flexural loading are beneficial to measure intrinsic properties of the composites [9-11].

Failure process is a very complex phenomenon for CFRP composite laminates. Different mode of failure, such as matrix yielding, matrix cracking, fiber/matrix interface debonding, fiber pull-out, fiber fracture and interface delamination could happen during the operational time. Interface delamination is one of the most critical issues face by the CFRP composite laminates due to the fact that most of composite

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